(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
21 October 2004 (21.10.2004)

PCT

(10) International Publication Number
WO 2004/090611 A2

(51) International Patent Classification[7]: G02C 7/00

(21) International Application Number: PCT/US2004/009736

(22) International Filing Date: 31 March 2004 (31.03.2004)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10/403,808 31 March 2003 (31.03.2003) US
10/703,884 7 November 2003 (07.11.2003) US

(71) Applicant *(for all designated States except US)*: **BAUSCH & LOMB INCORPORATED** [US/US]; One Bausch & Lomb Place, Rochester, NY 14604 (US).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: **ALTMAN, Griffith, E.** [US/US]; 88 Rock Creek, Pittsford, NY 14534 (US).

(74) Agents: **MCGUIRE, Katherine** et al.; Bausch & Lomb Incorporated, One Bausch & Lomb Place, Rochester, NY 14604 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

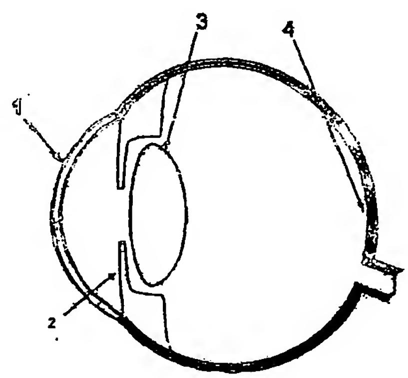
(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declaration under Rule 4.17:

— *as to the identity of the inventor (Rule 4.17(i)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD,*

[Continued on next page]

(54) Title: INTRAOCULAR LENS AND METHOD FOR REDUCING ABERRATIONS IN AN OCULAR SYSTEM



(57) Abstract: An intraocular lens for implantation in an eye. Transmission of a wavefront of light in a first wavelength range through the lens results in introduction of substantially no additional spherical aberration to the wavefront. According to one embodiment a lens body has first and second opposing surfaces each characterized by the same conic constant. In an associated method for reducing aberrations in an ocular system, a self-corrected intraocular lens is prepared with substantial correction to remove spherical aberrations which would otherwise be caused by the intraocular lens. Generally, in a method for focusing light in an eye, a wavefront of unaberrated light is provided at a corneal surface where it is transformed to aberrated light by transmission through the corneal surface. The wavefront is then transmitted through an intraocular lens implanted in the eye without introducing any substantial correction to the aberration introduced by the corneal surface.

WO 2004/090611 A2

SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW, ARIPO patent (BW, GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)

Published:

— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

INTRAOCULAR LENS AND METHOD FOR REDUCING ABERRATIONS IN AN OCULAR SYSTEM

FIELD OF THE INVENTION

The present invention relates to intraocular lenses and, in particular, to a lens design for improved vision.

BACKGROUND AND SUMMARY OF THE INVENTION

Intraocular lenses (IOLs) are commonly used in cataract surgery to improve vision. When the lens of the human eye develops a cataract which substantially impairs vision, the artificial lens is used in place of the natural lens to restore visual acuity. Although it is a desire in the art to provide the patient with better visual acuity than experienced in the pre-operative state, in practice such lens replacements typically do not fully or consistently replicate the performance of a natural lens. The IOL does not operate in the same manner as the natural lens, i.e., it does not have the ability to provide variable focusing capability by changing shape. Accordingly, a great deal of effort has been devoted to improving the performance of IOLs in order to approach the visual acuity attainable with the natural eye. In this regard, multifocal IOLs have been developed to provide correction for both near and far vision. See U.S. Nos. 5,089,024 and 6,210,005 each incorporated herein by reference.

It is desirable that IOL design include correction to improve contrast sensitivity, e.g., by accounting for aberrational phenomena. See, for example, U.S. Patent No. 6,224,211 which discloses use of aspheric IOLs to reduce spherical aberration of the

entire eye system. Further, attention has been directed to offsetting contributions of specific surfaces of the eye, e.g., the cornea, to minimize or eliminate wavefront aberrations. In this regard, see WO 01/89424 A1. Despite such efforts to correct for aberrations, IOL implants introduce other variables to the visual system that prevent many patients from realizing the theoretical performance that the modified eye system might otherwise provide. Ideally, it would be desirable to reduce the tolerance with which surgical procedures permanently center the IOL with respect to the optical axis. Better alignment capability would assure more optimal optical performance. In the absence of such improved capability other accommodations are sought.

The use of intraocular lenses (IOL) has become a common practice, especially for treating aphakic patients following a cataract removal surgery. Figure 1 represents a typical eye with cornea 1, iris 2, lens 3 and retina 4. An IOL is generically in the form of a spherical biconvex lens manufactures from one of polymethylmethacrylate (PMMA), silicone, or hydrogel. It replaces the eye's natural lens when it becomes damaged through one of two accepted surgical procedures. The first, and preferred, is the extracapsular extraction method, where the natural lens of the eye is removed while maintaining the integrity of at least the posterior portion of the capsular bag and preferably the anterior portion. This method allows for better centering and anchoring of the IOL in the eye, as the capsular bag remains anchored to the eyes ciliary body through the zonular fibers. The second extraction method is the intracapsular where the lens and the capsular bag are both removed entirely by severing the zonular fibers from the ciliary body. In this case the inserted IOL must be fixed in place through synthetic means. Figure 2 shows an aphakic eye with cornea 1, iris 2, IOL 5, and retina 4. The use of an

IOL provides a patient with a more natural solution than using either contact lenses or spectacles as the IOL stays in situ.

For many years surgeons were limited to inserting a monofocal IOL which because of its fixed focal length required the patient to then wear contacts or spectacles to achieve both near and far vision. Recently the introduction of bi-focal or more generally multi-focal IOLs has overcome this problem by creating a lens with multiple regions of varying power to give the patient some ability to see objects at different distances.

While recent IOLs have addressed the problems of near and far vision, further complications exist. These complications are typically in the form of higher order aberrations introduced into the aphakic eye, specifically astigmatism, coma, and spherical aberration (SA).

SA is common in any substantially spherical lens because peripheral light undergoes greater refraction than paraxial. Figure 3 demonstrates this effect, where a light rays 6 strike the periphery of a lens 7 are refracted more than rays 8 striking close to the optical axis of the lens. This changes the effective focal point of the lens resulting in observed images being blurry.

In the natural eye there are multiple sources of SA. The first is the cornea which creates under-corrected or negative SA. A natural lens typically creates overcorrected or positive SA which almost balances the negative SA from the cornea. However there is some under-corrected SA remaining which helps the eye to accommodate images at different distances through a dithering process. When the natural lens is replaced with an IOL, the SA is no longer always balanced. When using a spherical IOL or an IOL

having significant spherical regions the opposite occurs, additional under-corrected SA is created resulting in the aphakic eye having large amounts of under-corrected SA.

SA is also problematic in the manufacturing process of an IOL. A manufacturer must measure and report the paraxial power of a lens. Paraxial power is measured as the reciprocal of the effective focal length of the lens, with the effective focal length being the distance between the second principal surface of the lens and its paraxial focus. SA complicates this measurement as it blurs the focus with the plane of best focus no longer coinciding with the paraxial focus.

A specific embodiment shown in W.O. Patent No. 0189424 discloses an aspherical lens which strives to eliminate all SA in the aphakic eye. This is done by producing a lens which balances the SA created by the cornea through the creation of overcorrected SA in the lens. While the lens will correct the problems seen in a spherical IOL when inserted perfect in line with axis of vision, if tilted or decentered from the axis of vision in the eye, it will actually introduce additional aberrations such as coma and astigmatism. In the typical cataract removal surgery the IOL is decentered an average of 0.5mm.

DRAWINGS

Fig. 1 represents a typical human eye.

Fig. 2 shows an aphakic eye.

Fig. 3 is shows the effects of spherical aberration

Fig. 4 is a schematic cross section an eye system incorporating an intraocular lens constructed according to the invention.

Fig. 5 compares spherical to aspherical lenses.

Fig. 6 shows the lens of the invention inserted into an eye.

SUMMARY OF THE INVENTION

According to the invention there is now provided an intraocular lens for implantation in an eye wherein transmission of a wavefront of light in a first wavelength range through the lens results in introduction of substantially no additional spherical aberration to the wavefront. According to one embodiment a lens body has first and second opposing surfaces each characterized by the same conic constant. The lens may be formed of silicone.

In an associated method for reducing aberrations in an ocular system, a self-corrected intraocular lens is prepared with substantial correction to remove spherical aberrations which would otherwise be caused by the intraocular lens. The lens is inserted along the optical axis of an eye system comprising a cornea and a retinal surface. According to preferred embodiments of the method, images projected by the ocular

system include a net undercorrection of spherical aberration with the under correction primarily attributable to a positive spherical aberration introduced by transmission of light through the cornea. The intraocular lens may be displaced relative to the optical axis, e.g., in some embodiments up to 0.8 mm, without introducing substantial deterioration in visual acuity of the system. That is, the displaced intraocular lens does not introduce any substantial spherical aberrations to the ocular system.

Generally, in a method for focusing light in an eye a wavefront of unaberrated light is provided at a corneal surface where it is transformed to aberrated light by transmission through the corneal surface. The wavefront is then transmitted through an intraocular lens implanted in the eye without introducing any substantial correction to the aberration introduced by the corneal surface. In disclosed embodiments the wavefront transmitted through the intraocular lens is transmitted to a focal region near or on the retinal surface without substantially modifying the aberration introduced in the system by the corneal surface.

DETAILED DESCRIPTION OF THE INVENTION

When a spherical lens receives an unaberrated wave front the marginal rays (i.e., those rays impinging the lens near its edge) are known to refract more than the paraxial rays (those rays transmitted through a more central zone of the lens). A non-spherical lens may introduce a positive spherical aberration (termed an under-correction) or a negative spherical aberration (termed an over-correction).

The human eye is a lens system whose components can naturally be in close balance with one another with regard to spherical aberration. That is, the cornea

normally exhibits a positive spherical aberration and the lens at times provides a negative spherical aberration. In distance vision the net contribution will often be a slightly positive spherical aberration. For persons not in need of corrective lenses, the net result comes sufficiently close to and, in some instances achieves, a balance providing satisfactory net correction throughout the entire visual range.

At a young age it is more likely for an individual to achieve a full balance during accommodation, i.e., when the lens bends in order to focus close objects. As age progresses and the lens undergoes crystallization, a reduction in the ability of the lens to provide a negative contribution to spherical aberration occurs concurrently with the loss in ability to accommodate near objects. Consequently, the eye experiences a greater net positive spherical aberration, and this degradation may be most noticeable in near vision.

In the past, the surfaces of IOLs have, typically, been spherical. Accordingly, in an eye system, when the cornea receives an unaberrated wavefront, a first positive component of spherical aberration is introduced and transmitted to the positive power IOL. The IOL transforms the slightly aberrated wavefront to a more positively aberrated wavefront which propagates toward the retina. The resulting convergence of rays occurs over a somewhat distended focal region with the paraxial focal region occurring at the retina surface and the marginal focal region occurring substantially in front of the retina surface.

More recently, it has been proposed that the IOL include an over-correction to balance the positive spherical aberration introduced by the cornea. The correction may be based on the actual curvature of the cornea or on average or proximate values. See, again, WO 01/89424 A1. Although introduction of such a negative correction has been intended to provide an improved net balance it is now recognized, in accordance with the

present invention, that in many applications such a compensating benefit may be sub-optimal. According to the intended design such an IOL will introduce compensating spherical aberrations, but because the lens placement will rarely be on-center with the optical axis, some higher order aberrations, e.g., coma, will be introduced by the decentered IOL and this may noticeably degrade the visual acuity.

With reference to Figure 4, there is a human eye system 10 that comprises a corneal surface 12, an entrance pupil 14, an iris 16, an exemplary IOL 18 and a retinal surface 20, all symmetrically aligned along an optical axis 22. The IOL 18, formed of silicone, includes anterior and posterior opposing equiconic surfaces. The anterior equiconic surface 26 is a convex surface facing the corneal surface while the posterior equiconic surface 28 is a convex surface facing the retinal surface 20. Positions along the axis 22 are relative to the point at which the posterior surface 28 intersects the axis 22. Exemplary displacements orthogonal to the axis 22 are shown along a "y" axis. The surfaces 26, 28 each have a reduced sag, relative to a spherical shape, so that, overall, the lens is substantially corrected for spherical aberration in the visible spectrum.

Generally, the SAG for each surface 26, 28 may be based on the equation:

$$SAG = \frac{\frac{x^2}{R_v}}{1+\sqrt{1-(1+k)\frac{x^2}{R_v^2}}}$$

wherein x is the distance (measured from the point at which the surface intersects the axis 22, x = 0, to another point on the lens surface; R_v is the radius of the lens surface and k is the conic constant. Accordingly, Table 1 compares the attributes of the lens 18

with a prior art spherical lens. Each is an equiconvex lens formed of silicone with 20D power..

Table 1. Comparison of Attributes Between Prior Art Spherical Lens and IOL 18.

		Spherical	Aspherical
Refractive Index	Air	1.43	1.43
	Aqueous	1.336	1.336
Radii	Anterior	9.3575	9.3585
	Posterior	-9.3575	-9.3585
Conic Constant	Anterior	0	-1.17097
	Posterior	0	-1.17097
Lens Body Diameter	(mm)	6.0	6.0
Optic Zone Diameter		6.0	6.0
Edge Thickness		0.3	0.3
Center Thickness	(mm)	1.2879	1.2575
Cross-sectional Area	(mm^2)	5.773	5.627
Lens Volume	(mm^3)	22.575	21.999
Seidel Spherical Aberration Coefficient	(microns)	21.282	0.090

In the present invention at least one surface is aspherical to alter the refraction of peripheral rays of light in such a way to minimize spherical aberration (SA). Figure 5 illustrates the differences between a typical spherical IOL and the present invention in terms of their refractive properties. There a light ray 11 hitting the periphery of a spherical IOL 3 is not refracted onto the paraxial focus 13, causing SA. In comparison, a light ray 12 which strikes the periphery of the present invention IOL 18is refracted to the paraxial focus 13, limiting SA. Note that there is no difference in refraction for paraxial rays of light striking either lens.

Using aspherical rather than spherical surfaces creates a lens with very little SA. While this results in an aphakic eye with a net under-corrected spherical aberration, it

will be less than that resulting from using a spherical IOL. This is desirable, as a slight amount of remaining under-corrected SA in the aphakic eye gives depth of focus compensating for loss of accommodation. Likewise, removing the SA from the lens reduces the adverse impacts of decentering and tilt that are typical consequences in a cataract removal surgery. This prevents problems with coma and astigmatism that may result when the aberrations of the cornea are corrected. By ignoring the corneal spherical aberration, the resulting design is more forgiving and has a higher likelihood of success.

A feature of the IOL 18 and other embodiments according to the invention is that the IOL is not designed to eliminate aberrations introduced by an average cornea or a specific cornea. Rather, it is recognized that, because IOLs are typicaly decentered and tilted, those IOLs which introduce overcorrected spherical aberration (to fully compensate for undercorrection introduced by the cornea) will, in the typical off-axis orientation, introduce higher order aberrations including coma and astigmatism. After typical cataract surgeries, IOLs on average are decentered 0.5mm and tilted by about 3 degrees. Occasionally, the implanted IOL may be decentered as much as one mm and titled as much as 10 degrees. Accordingly, with complications resulting from such substantial decentering and tilt, it is not always beneficial to completely balance the otherwise undercorrected spherical aberration of the cornea. That is, effects of the off-axis IOL assymmetry may completely offset the intended benefit of on-axis correction that should otherwise compensate for aberrations created through the cornea. Higher order aberrations may also be prevalent.

Another feature of the invention relates to resulting systems such as drawn in Figure 1 wherein the IOL is ideally centered. Allowing the system 10 to remain undercorrected (with respect to the cornea contribution) is believed to compensate for the

system's loss in accommodation. That is, undercorrected spherical aberration by the cornea creates some depth of focus through which the brain may integrate and interpret data to better perceive edges which are not well focused. Patients who have had this depth of focus benefit (due to a net undercorrection) in their natural system may notice a loss of acuity if the corrected system removes the undercorrected spherical aberration of the cornea. With the system 10 such undercorrected, spherical aberration is allowed to remain, allowing the patient to process visual information in a manner similar to that experienced with the natural eye system.

Comparisons have been performed between the system 10 and a prior art construct formed with an IOL of the type that includes an over-correction to completely balance the positive spherical aberration introduced by the cornea when the IOL is fully aligned with the optical axis. In these comparisons correction in the prior art system was based on the actual curvature of the cornea. The performance distribution of the two systems was evaluated at three pupil openings (3mm, 4mm and 5mm), each as a function of random lens decentering for a population of 50 samples. The analysis assumed that all decentering occurred within two standard deviations, i.e., +/- 0.8mm relative to the optical axis. The shift of the retinal focal plane (relative to the on-axis position) was calculated for each member in each set of 50 random samples used to evaluate a system. The range in this shift was also determined for each 50 sample population. The RMS wavefront error was calculated for each sample and the maximum wavefront error was determined for 10 percent, 50 percent and 90 percent of each sample population.

With a 3mm pupil opening the prior art system exhibited up to a 50 micron displacement in the focal plane while the range in displacement for the system 10 was less than 3 microns. As pupil dilation increased the displacement in the focal plane

among population samples continued to range between 47 and 50 microns while the focal plane displacement for the system 10 also remained fairly stable, but increasing to no more than 5 microns. Thus the relative variability in focal plane displacement (as a function of decentering) appears minimal with the system 10.

More significantly, when compared to the prior art construct, the wavefront error of the system 10 was found to be significantly less while relatively stable at various pupil dilations. The wavefront error for the prior art construct increased substantially as pupil dilation increased. Degradation of the prior art construct is believed to be attributable to off-axis assymmetries. Such assymmetries are inherent in designs are intended to correct corneal aberrations in the context of substantial on-axis symmetry. Even at a 3 mm pupil opening the RMS wavefront error in the prior art construct was up to at least 0.036 (sigma = .0125) for the 10 percent of the sample having the least decentering. When the 10 percent of the sample having the greatest decentering was removed from the group the range of the RMS wavefront error increased up to at least .055 (sigma = 0.0125). In contrast, the maximum RMS wavefront error for the system 10 of the invention at the same 3 mm pupil opening only ranged from about 0.026 (sigma = 0.00121), for the 10 percent of the population having the least decentering, up to less than .029 (sigma = 0.00121) among the entire sample population.

With a 4 mm pupil opening the RMS wavefront error in the prior art construct increased up to at least 0.119 (sigma = 0.0223) for the 10 percent of the sample having the least decentering and, when the 10 percent of the sample having the greatest decentering was removed from the group, the range of the RMS wavefront error further increased up to at least 0.160 (sigma = 0.0223). In contrast, the maximum RMS wavefront error for the system 10 at the same 4 mm pupil opening only ranged from

about 0.026 (sigma = 0.00166), for the 10 percent of the population having the least decentering, up to less than .029 (sigma = 0.00166) among the entire sample population.

With a 5 mm pupil opening the RMS wavefront error in the prior art construct increased up to at least 0.301 (sigma = 0.0376) for the 10 percent of the sample having the least decentering and, when the 10 percent of the sample having the greatest decentering was removed from the group, the range of the RMS wavefront error further increased up to at least 0.376 (sigma = 0.0376). In contrast, the maximum RMS wavefront error for the system 10 at the same 4 mm pupil opening only ranged from about 0.206 (sigma = 0.00373), for the 10 percent of the population having the least decentering, up to less than .220 (sigma = 0.00373) among the entire sample population.

Table 2 summarizes the comparative results discussed above. Notice that for all portions of the population use of the invention IOL results in significantly lower RMS wave front errors. Likewise the compensation ranges are all smaller for the invention IOL when compared to the typical spherical IOL. The smaller RMS wavefront error is an indication that the invention will be less likely to cause coma and astigmatism when decentered compared to a typical spherical IOL. The smaller compensation ranges indicate that the invention IOL will be more likely to correct a patient's vision even when decentered from the axis of vision.

Table 2 Comparison of Spherical and Aspherical IOL.

Pupil Entrance Diameter (mm)		RMS Wavefront Error 90%	50%	10%	Compensation (µm) Range
3	Typical	0.0557	0.0420	0.0373	50.17
	Invention	0.0286	0.0258	0.0254	2.68
4	Typical	0.1689	0.1284	0.1199	49.10
	Invention	0.0860	0.0832	0.0821	3.17
5	Typical	0.3761	0.3149	0.3018	47.62
	Invention	0.2169	0.2080	0.2063	3.84

The above results suggest that when an IOL which is self-corrected for aspherical aberration is placed in an ocular system the optical performance can exceed that which results from placement of an IOL designed to remove substantially all net aspherical aberration from the system.

Referring to Figure 6, the present invention IOL 18 will be inserted into the eye of a patient to replace the natural lens. Rays of light 15 entering the eye will pass through the cornea 1 and be refracted according the Snell's Law. As the cornea is substantially spherical, there will be under-corrected SA. Next the ray of light will pass through the IOL 18 and be refracted again according the Snell's Law. As the present invention has no SA, the net SA of the aphakic eye will be unchanged from that generated by the cornea. Finally the ray of light will strike the retina creating an image.

Although limited embodiments of the invention have been illustrated, numerous modifications and variations will be apparent to those skilled in the art. For example, numerous types of lens designs may be used to construct an IOL according to the invention, including rigid biocompatible materials such as polymthylmethacrylate (PMMA) and flexible, deformable material, such as acrylic polymerics, hydrogels and the like which permit the IOL to be deformed for ease of insertion into a minimally sized surgical incision.

A biconvex lens has been illustrated but it will also be understood that the concepts disclosed herein may be practiced with plane convex designs. The IOL may be of the multifocal design type, in which case the principles taught herein could be separately applied to differing zones (e.g., near, intermediate and distant).

Another advantage of the IOL disclosed herein is that by incorporating a conic constant less than zero (to self-correct the lens for spherical aberrations), the resulting lens profile is thinner than that of a spherical lens such as described in Table 1. Note that the aspherical lens of Table 1 has a smaller center thickness, a smaller cross-sectional area and a smaller volume than the prior art spherical lens to which it is compared. The smaller profile can be advantageous when surgically inserting the IOL into an opening of minimal width. The smaller volume can result in lower net weight for the optic, which may help minimize decentering of the optic once it is inserted.

It should also be understood that the examples provided herein are based on approximations, specific lens powers (22D) and wavelengths (.555 nm). These examples are only intended to illustrate relative benefits achievable with the invention. Reference to the IOL 10 as having been corrected to remove spherical aberrations is intended to mean that there is a relative correction resulting in substantial but not necessarily entire elimination of such aberrations. Further, while analyses of performance have not been made at all visible wavelengths, it will be understood by those skilled in the art that variations are contemplated as a function of the wavelength and such factors should be considered when designing an IOL according to the invention.

It is also to be recognized that, while the preferred embodiments result in an intraocular lens that provides no noticeable correction to compensate for spherical aberration created by a corneal surface, the scope of the invention contemplates IOL

designs which could provide some minor (perhaps up to 50 percent) under-correction relative to the over-correction exhibited by a cornea. Accordingly, the IOL may provide some minor correction that could partially offset under-correction resulting from a cornea in an eye system in which the lens may be implanted. Notwithstanding such provision of minor correction for corneal aberration, it is contemplated that the IOL can nonetheless provide some beneficial improvement in systems where the IOL is decentered or tilted relative to the optical axis.

Accordingly, the scope of the invention is only to be limited by the claims which now follow.

I claim:

1. An intraocular lens for implantation in an eye, comprising:

a lens body having first and second opposing surfaces with at least one of the surfaces characterized by a predetermined conic constant such that transmission of a wavefront of light in a first wavelength range through the lens results in introduction of substantially no additional spherical aberration to the wavefront.

2. The lens of claim 1 wherein the first and second surfaces are characterized by the same conic constant.

3. The lens of claim 1 wherein the first and second surfaces are equiconvex.

4. The lens of claim 1 wherein the body predominantly comprises silicone.

5. The lens of claim 1 wherein substantially no additional spherical correction means less correction than would be needed to balance undercorrection resulting from a corneal surface of an eye system in which the lens may be implanted.

6. An intraoccular lens incorporating correction along a surface thereof to substantially avoid introduction of spherical aberration to a wavefront transmitted therethrough.

7. The lens of claim 6 wherein the lens provides less than 50 percent overcorrection relative to an undercorrected cornea.

8. An intraocular lens having at least one aspherical surface with a conical constant less than zero, said lens having a correction to substantially avoid spherical aberration of light transmitted therethrough.

9. The lens of claim 8 adapted for application in an eye system including a cornea wherein the correction does not substantially compensate for undercorrection created by the cornea.

10. The lens of claim 9 wherein the correction compensates for less than 50 percent of the undercorrection created by the cornea.

11. The lens of claim 9 wherein the correction compensates for essentially none of the undercorrection created by the cornea.

12. A method for reducing aberrations in an ocular system comprising:

preparing a self-corrected intraocular lens having substantial correction to remove spherical aberrations which would otherwise be caused by the intraocular lens; and

inserting the intraocular lens along the optical axis of an eye system comprising a cornea and a retinal surface.

13. The method of claim 12 wherein images projected by the ocular system include a net undercorrection of spherical aberration.

14. The method of claim 13 wherein the net under correction is primarily attributable to a positive spherical aberration introduced by transmission of light through the cornea.

15. The method of claim 12 further including the step of allowing the intraocular lens to displace relative to the optical axis.

16. The method of claim 15 wherein the displaced intraocular lens does not introduce any substantial spherical aberrations to the ocular system.

17. The method of claim 15 wherein the displaced intraocular lens creates substantially no coma in the ocular system.

18. The method of claim 15 wherein the displaced intraocular lens creates substantially no astigmatism in the ocular system.

19. A method for focusing light in an eye comprising the steps of :

providing a wavefront of unaberrated light to a corneal surface;

transforming the wavefront to aberrated light by transmitting the light through the corneal surface; and

transmitting the wavefront through an intraocular lens implanted in the eye without introducing any substantial correction to the aberration introduced by the corneal surface.

20. The method of claim 19 wherein the wavefront transmitted through the intraocular lens is transmitted to a focal region near or on the retinal surface without substantially modifying the aberration introduced in the system by the corneal surface.

21. An intraoccular lens for implantation in an eye, comprising:

an optical lens body having first and second opposing surfaces for transmitting light through the lens body to a desired focal region, with at least one of said first and second surfaces having a reduced sag so that the lens is substantially corrected for spherical aberration in the visible spectrum.

22. The lens of claim 21 optimally corrected to prevent spherical aberration of light having a wavelength of .555 nm.

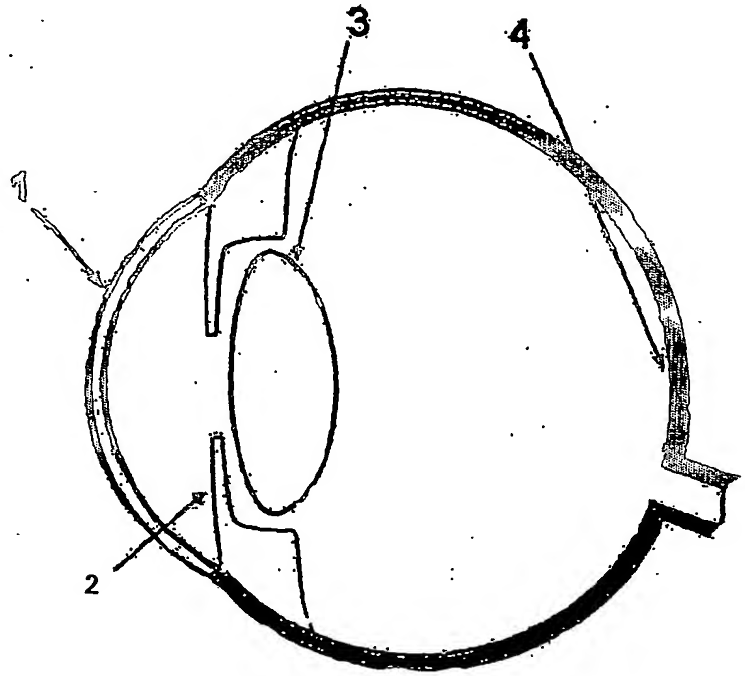


Figure 1

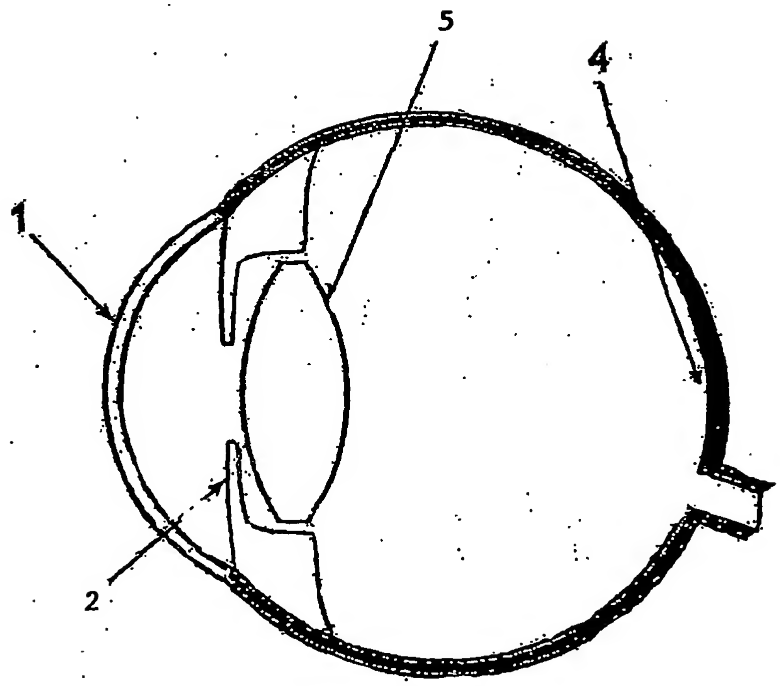


Figure 2 Prior Art

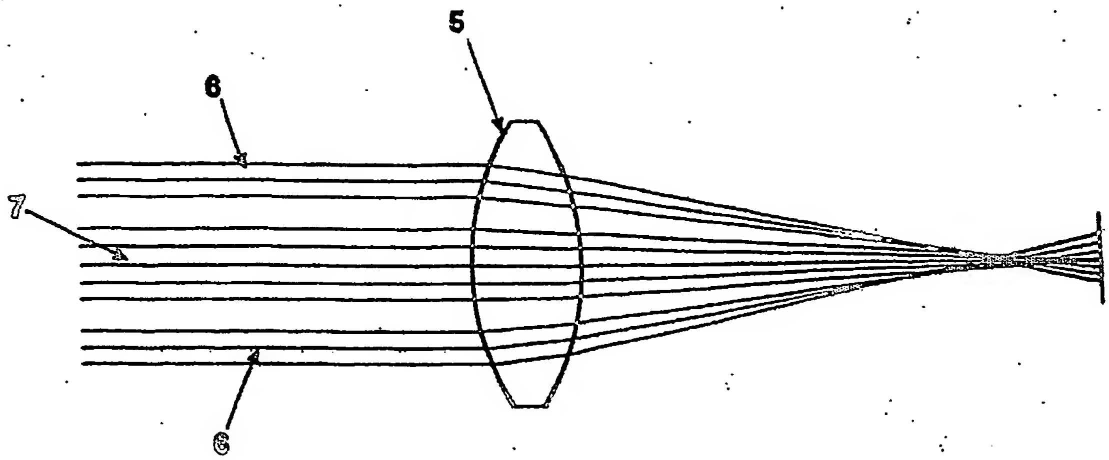


Figure 3

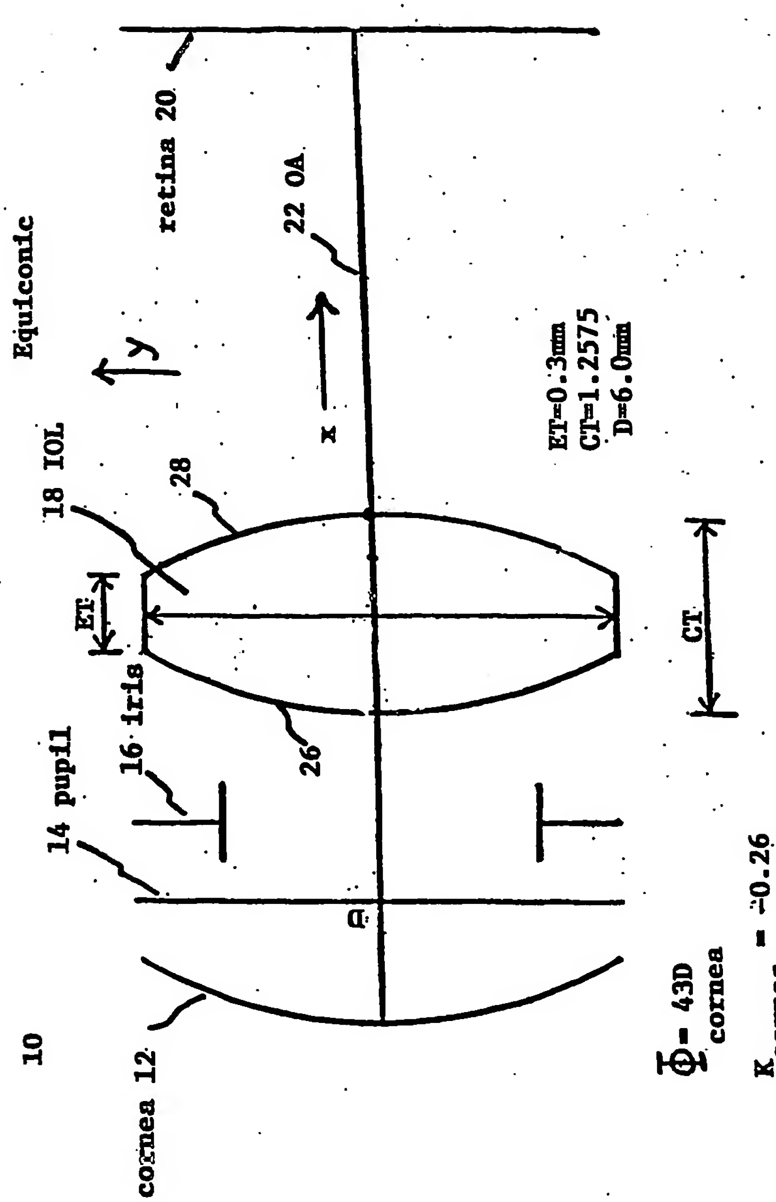

Equiconic
10
cornea 12
14 pupil
16 iris
18 IOL
26
28
ET
CT
retina 20
22 OA
x
y
ET=0.3mm
CT=1.2575
D=6.0mm
Φ_{cornea} = 43D
K_{cornea} = -0.26

Figure 4

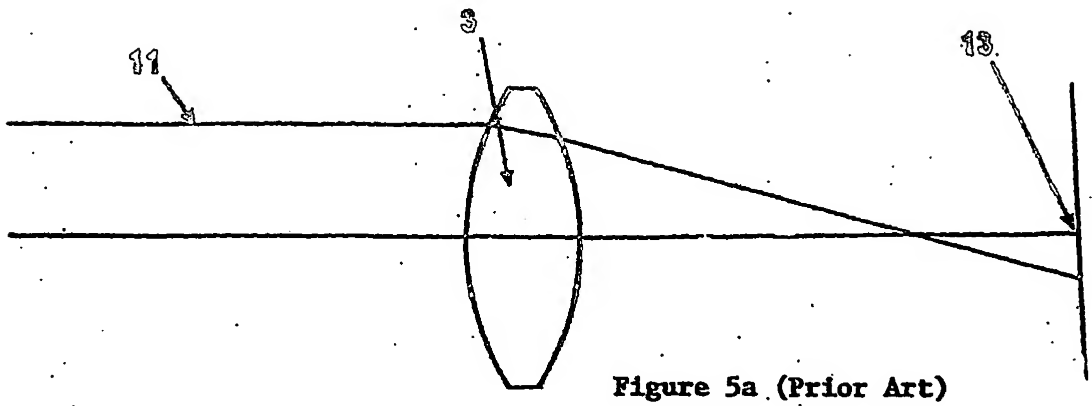


Figure 5a (Prior Art)

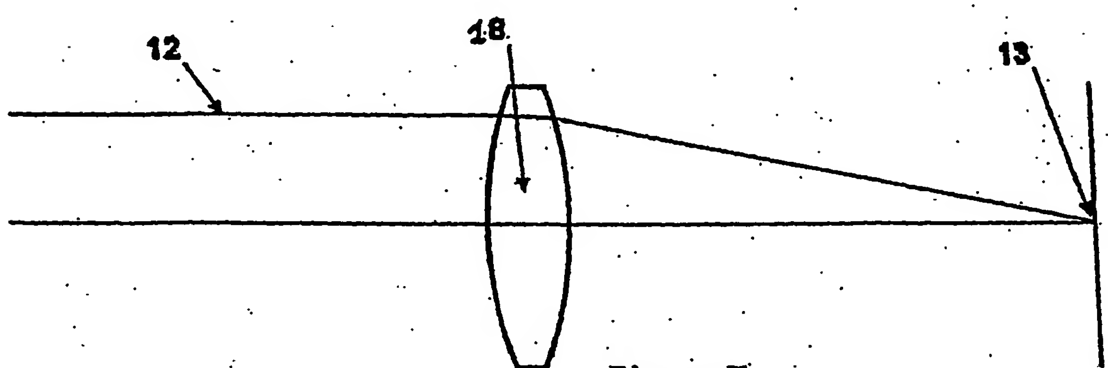


Figure 5b

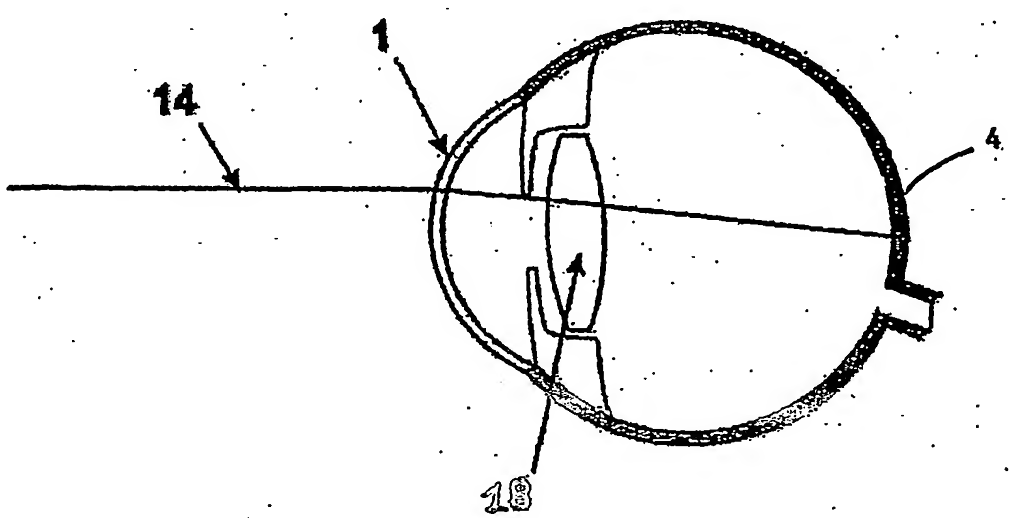


Figure 6

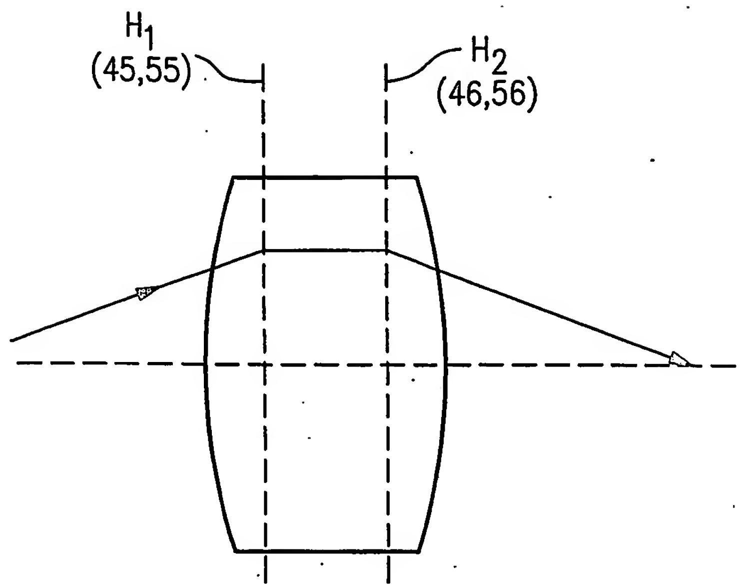


FIG.7a

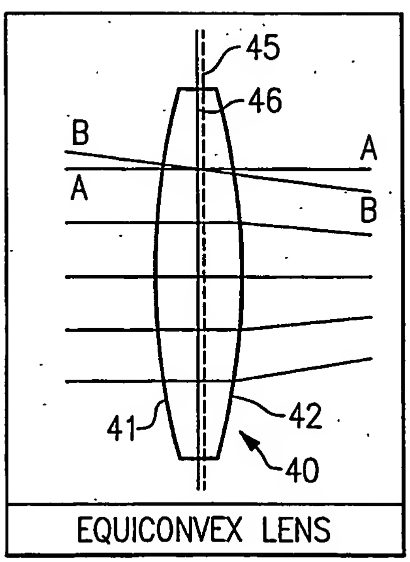


FIG.7b

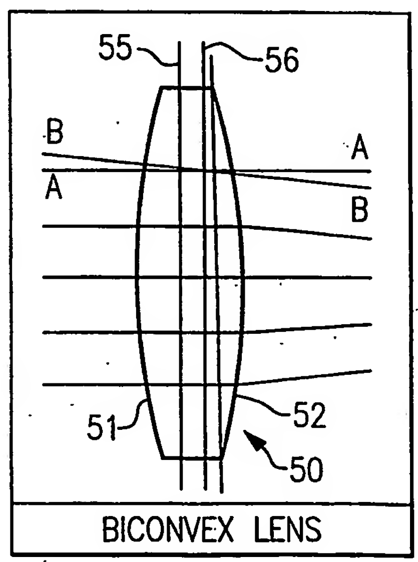


FIG.7c

00005057.DOC

EQUICONVEX SPHERICAL LENS FAMILY
Nm = 1.427 Na = 1.336

Power (diopter)	Ra (mm)	Rp (mm)	CT (mm)	ET (mm)	E2H2 (mm) (Y/Fig 13)	Effect of H2 Position (diopter)	SA (D) Equi-convex Sphere (diopter) (Y/ Fig 12)	Effect of SA (diopter)	A-const Delta Equiconvex (diopter)
10	18.174	-18.174	0.799	0.300	-0.125	-0.008	0.020	0.140	0.132
10.5	17.307	-17.307	0.824	0.300	-0.124	-0.008	0.023	0.137	0.128
11	16.518	-16.518	0.849	0.300	-0.124	-0.008	0.026	0.133	0.125
11.5	15.798	-15.798	0.875	0.300	-0.123	-0.008	0.030	0.129	0.121
12	15.138	-15.138	0.900	0.300	-0.122	-0.008	0.034	0.125	0.117
12.5	14.530	-14.530	0.926	0.300	-0.121	-0.008	0.039	0.121	0.113
13	13.970	-13.970	0.952	0.300	-0.121	-0.008	0.044	0.116	0.108
13.5	13.450	-13.450	0.978	0.300	-0.120	-0.008	0.049	0.111	0.103
14	12.968	-12.968	1.004	0.300	-0.119	-0.007	0.054	0.105	0.098
14.5	12.519	-12.519	1.030	0.300	-0.118	-0.007	0.060	0.099	0.092
15	12.100	-12.100	1.056	0.300	-0.118	-0.007	0.067	0.093	0.086
15.5	11.707	-11.707	1.082	0.300	-0.117	-0.006	0.074	0.086	0.079
16	11.340	-11.340	1.108	0.300	-0.116	-0.006	0.081	0.078	0.072
16.5	10.994	-10.994	1.134	0.300	-0.116	-0.005	0.089	0.070	0.065
17	10.669	-10.669	1.161	0.300	-0.115	-0.005	0.098	0.062	0.057
17.5	10.362	-10.362	1.188	0.300	-0.114	-0.004	0.107	0.053	0.049
18	10.072	-10.072	1.214	0.300	-0.113	-0.003	0.116	0.043	0.040
18.5	9.798	-9.798	1.241	0.300	-0.113	-0.002	0.126	0.033	0.031
19	9.538	-9.538	1.268	0.300	-0.112	-0.002	0.137	0.023	0.021
19.5	9.292	-9.292	1.295	0.300	-0.111	-0.001	0.148	0.012	0.011
20	9.058	-9.058	1.322	0.300	-0.111	0.000	0.160	0.000	0.000
20.5	8.835	-8.835	1.350	0.300	-0.110	0.001	0.172	-0.012	-0.011
21	8.623	-8.623	1.377	0.300	-0.109	0.002	0.185	-0.025	-0.023
21.5	8.420	-8.420	1.405	0.300	-0.109	0.003	0.198	-0.039	-0.036
22	8.227	-8.227	1.433	0.300	-0.108	0.004	0.213	-0.053	-0.049
22.5	8.042	-8.042	1.461	0.300	-0.107	0.005	0.228	-0.068	-0.063
23	7.865	-7.865	1.489	0.300	-0.107	0.006	0.243	-0.084	-0.077
23.5	7.696	-7.696	1.518	0.300	-0.106	0.007	0.259	-0.100	-0.093
24	7.534	-7.534	1.546	0.300	-0.105	0.009	0.276	-0.117	-0.108
24.5	7.378	-7.378	1.575	0.300	-0.105	0.010	0.294	-0.135	-0.125
25	7.228	-7.228	1.604	0.300	-0.104	0.011	0.313	-0.153	-0.142
25.5	7.085	-7.085	1.633	0.300	-0.104	0.012	0.332	-0.172	-0.160
26	6.947	-6.947	1.662	0.300	-0.103	0.014	0.352	-0.192	-0.179
26.5	6.814	-6.814	1.692	0.300	-0.102	0.015	0.373	-0.213	-0.198
27	6.685	-6.685	1.722	0.300	-0.102	0.017	0.394	-0.235	-0.218
27.5	6.562	-6.562	1.752	0.300	-0.101	0.018	0.417	-0.257	-0.239
28	6.443	-6.443	1.782	0.300	-0.101	0.020	0.440	-0.280	-0.261
28.5	6.328	-6.328	1.813	0.300	-0.100	0.021	0.464	-0.305	-0.284
29	6.217	-6.217	1.844	0.300	-0.099	0.023	0.489	-0.330	-0.307
29.5	6.109	-6.109	1.875	0.300	-0.099	0.024	0.515	-0.355	-0.331
30	6.005	-6.005	1.906	0.300	-0.098	0.026	0.542	-0.382	-0.356

FIG. 8

00005057.DOC

BICONVEX SPHERICAL LENS FAMILY

Nm = 1.427 Na = 1.336

Power (diopter)	Ra (mm)	Rp (mm)	CT (mm)	ET (mm)	E2H2 (mm) (Y/Fig. 13)	Biconvex (Ra:Rp = 1:2) (diopter)	Power Delta Equi-convex Sphere (diopter) (Y/Fig 11)
10	13.633	-27.266	0.800	0.300	-0.334	0.095	-0.036
10.5	12.982	-25.965	0.825	0.300	-0.342	0.097	-0.032
11	12.391	-24.782	0.851	0.300	-0.350	0.098	-0.027
11.5	11.851	-23.702	0.877	0.300	-0.357	0.098	-0.023
12	11.356	-22.712	0.902	0.300	-0.365	0.098	-0.019
12.5	10.900	-21.800	0.928	0.300	-0.373	0.097	-0.016
13	10.480	-20.959	0.954	0.300	-0.381	0.095	-0.013
13.5	10.090	-20.180	0.981	0.300	-0.389	0.093	-0.010
14	9.729	-19.457	1.007	0.300	-0.397	0.090	-0.007
14.5	9.392	-18.784	1.033	0.300	-0.405	0.087	-0.005
15	9.077	-18.155	1.060	0.300	-0.413	0.083	-0.003
15.5	8.783	-17.567	1.086	0.300	-0.422	0.078	-0.002
16	8.508	-17.015	1.113	0.300	-0.430	0.072	0.000
16.5	8.248	-16.497	1.140	0.300	-0.439	0.066	0.001
17	8.005	-16.009	1.167	0.300	-0.447	0.059	0.001
17.5	7.775	-15.549	1.194	0.300	-0.456	0.051	0.002
18	7.557	-15.115	1.222	0.300	-0.464	0.042	0.002
18.5	7.352	-14.703	1.249	0.300	-0.473	0.033	0.002
19	7.157	-14.314	1.277	0.300	-0.482	0.023	0.002
19.5	6.972	-13.944	1.305	0.300	-0.491	0.012	0.001
20	6.797	-13.593	1.333	0.300	-0.500	0.000	0.000
20.5	6.629	-13.259	1.361	0.300	-0.510	-0.013	-0.001
21	6.470	-12.941	1.390	0.300	-0.519	-0.026	-0.003
21.5	6.319	-12.637	1.419	0.300	-0.529	-0.041	-0.005
22	6.174	-12.347	1.448	0.300	-0.538	-0.056	-0.007
22.5	6.035	-12.070	1.477	0.300	-0.548	-0.072	-0.009
23	5.903	-11.805	1.507	0.300	-0.558	-0.090	-0.012
23.5	5.776	-11.551	1.537	0.300	-0.568	-0.108	-0.015
24	5.654	-11.308	1.567	0.300	-0.578	-0.127	-0.019
24.5	5.537	-11.075	1.597	0.300	-0.589	-0.148	-0.023
25	5.425	-10.850	1.628	0.300	-0.600	-0.169	-0.027
25.5	5.317	-10.635	1.659	0.300	-0.610	-0.192	-0.032
26	5.214	-10.428	1.690	0.300	-0.622	-0.216	-0.037
26.5	5.114	-10.228	1.722	0.300	-0.633	-0.241	-0.043
27	5.018	-10.036	1.754	0.300	-0.644	-0.267	-0.049
27.5	4.925	-9.851	1.787	0.300	-0.656	-0.295	-0.056
28	4.836	-9.672	1.820	0.300	-0.668	-0.324	-0.063
28.5	4.750	-9.499	1.853	0.300	-0.680	-0.355	-0.071
29	4.666	-9.333	1.887	0.300	-0.693	-0.387	-0.080
29.5	4.586	-9.172	1.922	0.300	-0.706	-0.421	-0.089
30	4.508	-9.016	1.957	0.300	-0.719	-0.456	-0.099

FIG. 9

00005057.DOC
BICONVEX ASPHERICAL LENS FAMILY
Nm = 1.427 Na = 1.336 SA = 0 Ka = Kp = -0.97799

Power (diopter)	Ra (mm)	Rp (mm)	CT (mm)	ET (mm)	E2H2 (mm) (Y/Fig. 13)	Effect of H2 Position (diopter)	Biconvex Asphere (Ra:Rp = 1:2) (diopter)	Power Delta Equi-convex Sphere (diopter) (Y/Fig. 11)
10	13.633	-27.266	0.795	0.300	-0.332	0.085	0.180	-0.047
10.5	12.983	-25.965	0.820	0.300	-0.339	0.086	0.182	-0.043
1	12.391	-24.782	0.845	0.300	-0.347	0.086	0.183	-0.039
11.5	11.851	-23.702	0.870	0.300	-0.354	0.086	0.183	-0.035
12	11.356	-22.712	0.895	0.300	-0.361	0.086	0.182	-0.031
12.5	10.900	-21.801	0.919	0.300	-0.368	0.085	0.180	-0.028
13	10.480	-20.960	0.944	0.300	-0.376	0.083	0.176	-0.025
13.5	10.090	-20.181	0.969	0.300	-0.383	0.081	0.171	-0.022
14	9.729	-19.458	0.994	0.300	-0.391	0.078	0.165	-0.020
14.5	9.392	-18.784	1.019	0.300	-0.398	0.075	0.158	-0.017
15	9.078	-18.156	1.044	0.300	-0.405	0.071	0.150	-0.015
15.5	8.784	-17.567	1.069	0.300	-0.413	0.066	0.140	-0.013
16	8.508	-17.016	1.094	0.300	-0.420	0.061	0.130	-0.011
16.5	8.249	-16.498	1.119	0.300	-0.427	0.056	0.118	-0.009
17	8.005	-16.010	1.144	0.300	-0.435	0.049	0.104	-0.008
17.5	7.775	-15.550	1.169	0.300	-0.442	0.043	0.090	-0.006
18	7.558	-15.116	1.194	0.300	-0.450	0.035	0.074	-0.005
18.5	7.352	-14.705	1.219	0.300	-0.457	0.027	0.058	-0.004
19	7.158	-14.315	1.244	0.300	-0.465	0.019	0.040	-0.002
19.5	6.973	-13.946	1.269	0.300	-0.472	0.010	0.020	-0.001
20	6.797	-13.595	1.294	0.300	-0.480	0.000	0.000	0.000
20.5	6.630	-13.261	1.319	0.300	-0.487	-0.010	-0.022	0.001
21	6.471	-12.943	1.344	0.300	-0.495	-0.021	-0.045	0.002
21.5	6.320	-12.639	1.369	0.300	-0.502	-0.033	-0.069	0.003
22	6.175	-12.350	1.394	0.300	-0.510	-0.045	-0.094	0.005
22.5	6.036	-12.073	1.419	0.300	-0.517	-0.057	-0.121	0.006
23	5.904	-11.808	1.445	0.300	-0.525	-0.071	-0.149	0.007
23.5	5.777	-11.554	1.470	0.300	-0.533	-0.084	-0.178	0.008
24	5.656	-11.311	1.495	0.300	-0.540	-0.099	-0.208	0.009
24.5	5.539	-11.078	1.520	0.300	-0.548	-0.114	-0.240	0.011
25	5.427	-10.854	1.545	0.300	-0.556	-0.130	-0.272	0.012
25.5	5.319	-10.639	1.571	0.300	-0.563	-0.146	-0.306	0.014
26	5.216	-10.432	1.596	0.300	-0.571	-0.163	-0.342	0.016
26.5	5.116	-10.232	1.621	0.300	-0.579	-0.180	-0.378	0.018
27	5.020	-10.041	1.647	0.300	-0.587	-0.198	-0.416	0.020
27.5	4.928	-9.856	1.672	0.300	-0.594	-0.217	-0.455	0.022
28	4.839	-9.677	1.697	0.300	-0.602	-0.236	-0.496	0.024
28.5	4.753	-9.505	1.723	0.300	-0.610	-0.256	-0.538	0.027
29	4.669	-9.339	1.748	0.300	-0.618	-0.277	-0.581	0.030
29.5	4.589	-9.178	1.773	0.300	-0.626	-0.298	-0.625	0.033
30	4.511	-9.023	1.799	0.300	-0.633	-0.320	-0.670	0.036

FIG. 10

00005057.DOC
EQUICONVEX ASPHERE LENS FAMILY
Nm = 1.427 Na = 1.336 SA = 0 Ka = Kp = -1.16133 SA = 0

Power	Ra	Rp	CT	ET	E2H2	Effect of H2 Position	Equiconic (Ra:Rp = 1:1)	Power Delta Equi-convex Sphere (Y/Fig. 11)
(diopter)	(mm)	(mm)	(mm)	(mm)	(mm)	(diopter)	(diopter)	(diopter)
10	18.175	-18.175	0.795	0.300	-0.125	-0.008	-0.008	-0.139
10.5	17.307	-17.307	0.819	0.300	-0.124	-0.008	-0.008	-0.136
11	16.518	-16.518	0.844	0.300	-0.124	-0.008	-0.008	-0.133
11.5	15.798	-15.798	0.869	0.300	-0.123	-0.008	-0.008	-0.129
12	15.138	-15.138	0.894	0.300	-0.122	-0.008	-0.008	-0.125
12.5	14.531	-14.531	0.918	0.300	-0.122	-0.008	-0.008	-0.120
13	13.970	-13.970	0.943	0.300	-0.121	-0.007	-0.007	-0.115
13.5	13.451	-13.451	0.968	0.300	-0.120	-0.007	-0.007	-0.110
14	12.968	-12.968	0.993	0.300	-0.119	-0.007	-0.007	-0.105
14.5	12.519	-12.519	1.017	0.300	-0.119	-0.007	-0.007	-0.099
15	12.100	-12.100	1.042	0.300	-0.118	-0.006	-0.006	-0.092
15.5	11.708	-11.708	1.067	0.300	-0.117	-0.006	-0.006	-0.085
16	11.340	-11.340	1.091	0.300	-0.117	-0.005	-0.005	-0.078
16.5	10.995	-10.995	1.116	0.300	-0.116	-0.005	-0.005	-0.070
17	10.669	-10.669	1.141	0.300	-0.115	-0.004	-0.004	-0.061
17.5	10.363	-10.363	1.166	0.300	-0.115	-0.004	-0.004	-0.053
18	10.073	-10.073	1.190	0.300	-0.114	-0.003	-0.003	-0.043
18.5	9.799	-9.799	1.215	0.300	-0.114	-0.002	-0.002	-0.033
19	9.539	-9.539	1.240	0.300	-0.113	-0.002	-0.002	-0.023
19.5	9.293	-9.293	1.264	0.300	-0.112	-0.001	-0.001	-0.012
20	9.059	-9.059	1.289	0.300	-0.112	0.000	0.000	0.000
20.5	8.836	-8.836	1.314	0.300	-0.111	0.001	0.001	0.012
21	8.624	-8.624	1.339	0.300	-0.110	0.002	0.002	0.025
21.5	8.421	-8.421	1.363	0.300	-0.110	0.003	0.003	0.039
22	8.228	-8.228	1.388	0.300	-0.109	0.004	0.004	0.053
22.5	8.044	-8.044	1.413	0.300	-0.109	0.005	0.005	0.067
23	7.867	-7.867	1.437	0.300	-0.108	0.005	0.005	0.083
23.5	7.698	-7.698	1.462	0.300	-0.108	0.007	0.007	0.099
24	7.536	-7.536	1.487	0.300	-0.107	0.008	0.008	0.116
24.5	7.380	-7.380	1.511	0.300	-0.106	0.009	0.009	0.133
25	7.231	-7.231	1.536	0.300	-0.106	0.010	0.010	0.152
25.5	7.087	-7.087	1.561	0.300	-0.105	0.011	0.011	0.171
26	6.949	-6.949	1.586	0.300	-0.105	0.012	0.012	0.191
26.5	6.816	-6.816	1.610	0.300	-0.104	0.013	0.013	0.211
27	6.688	-6.688	1.635	0.300	-0.104	0.014	0.014	0.233
27.5	6.565	-6.565	1.660	0.300	-0.103	0.016	0.016	0.255
28	6.446	-6.446	1.684	0.300	-0.103	0.017	0.017	0.278
28.5	6.331	-6.331	1.709	0.300	-0.102	0.018	0.018	0.302
29	6.220	-6.220	1.734	0.300	-0.102	0.019	0.019	0.326
29.5	6.113	-6.113	1.758	0.300	-0.102	0.021	0.021	0.352
30	6.009	-6.009	1.783	0.300	-0.101	0.022	0.022	0.378

FIG.11

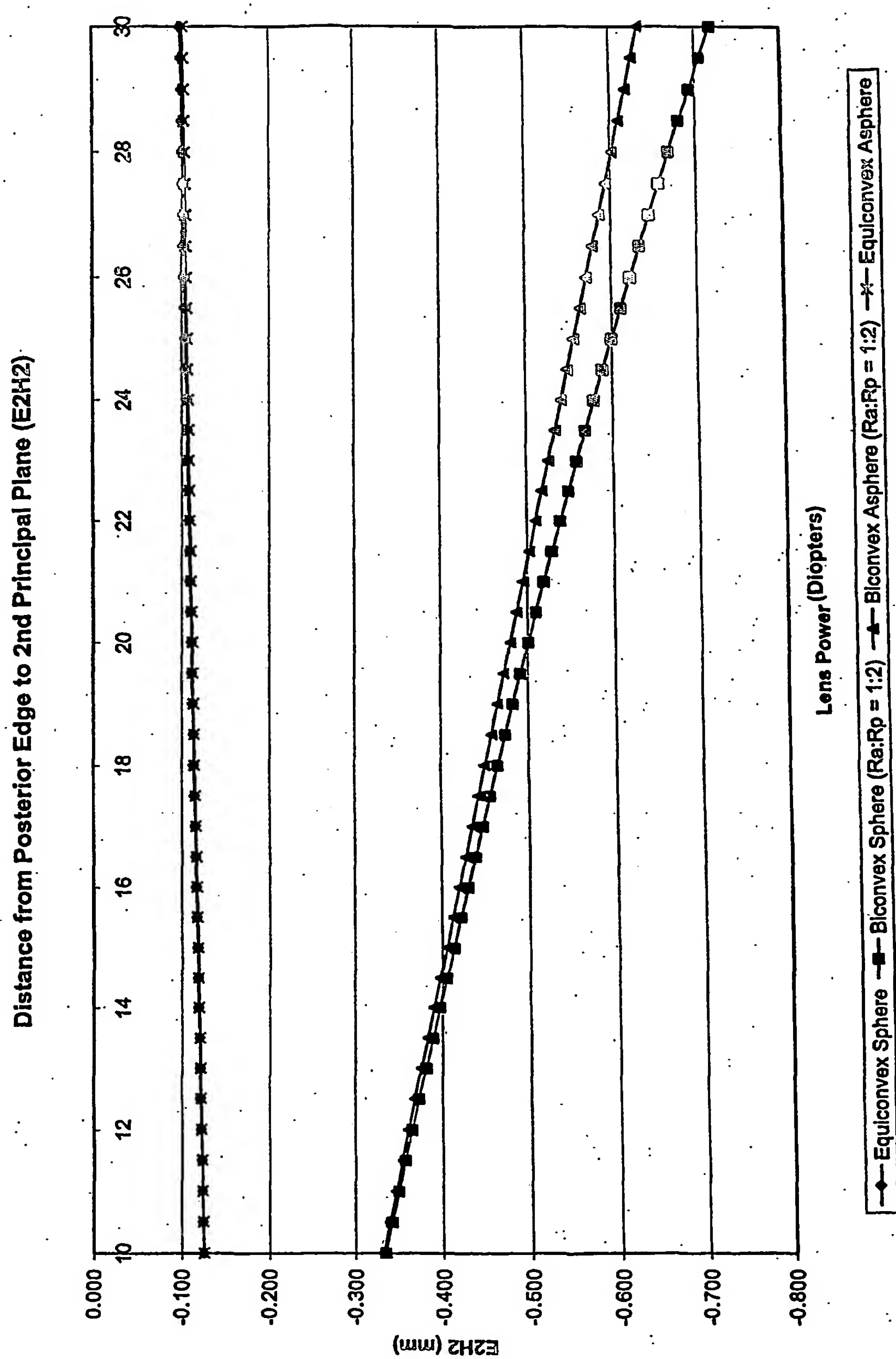

Distance from Posterior Edge to 2nd Principal Plane (E2H2)
E2H2 (mm)
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
-0.600
-0.700
-0.800
10
12
14
16
18
20
22
24
26
28
30
Lens Power (Diopters)
Equiconvex Sphere
Biconvex Sphere (Ra:Rp = 1:2)
Biconvex Asphere (Ra:Rp = 1:2)
Equiconvex Asphere

FIG. 12

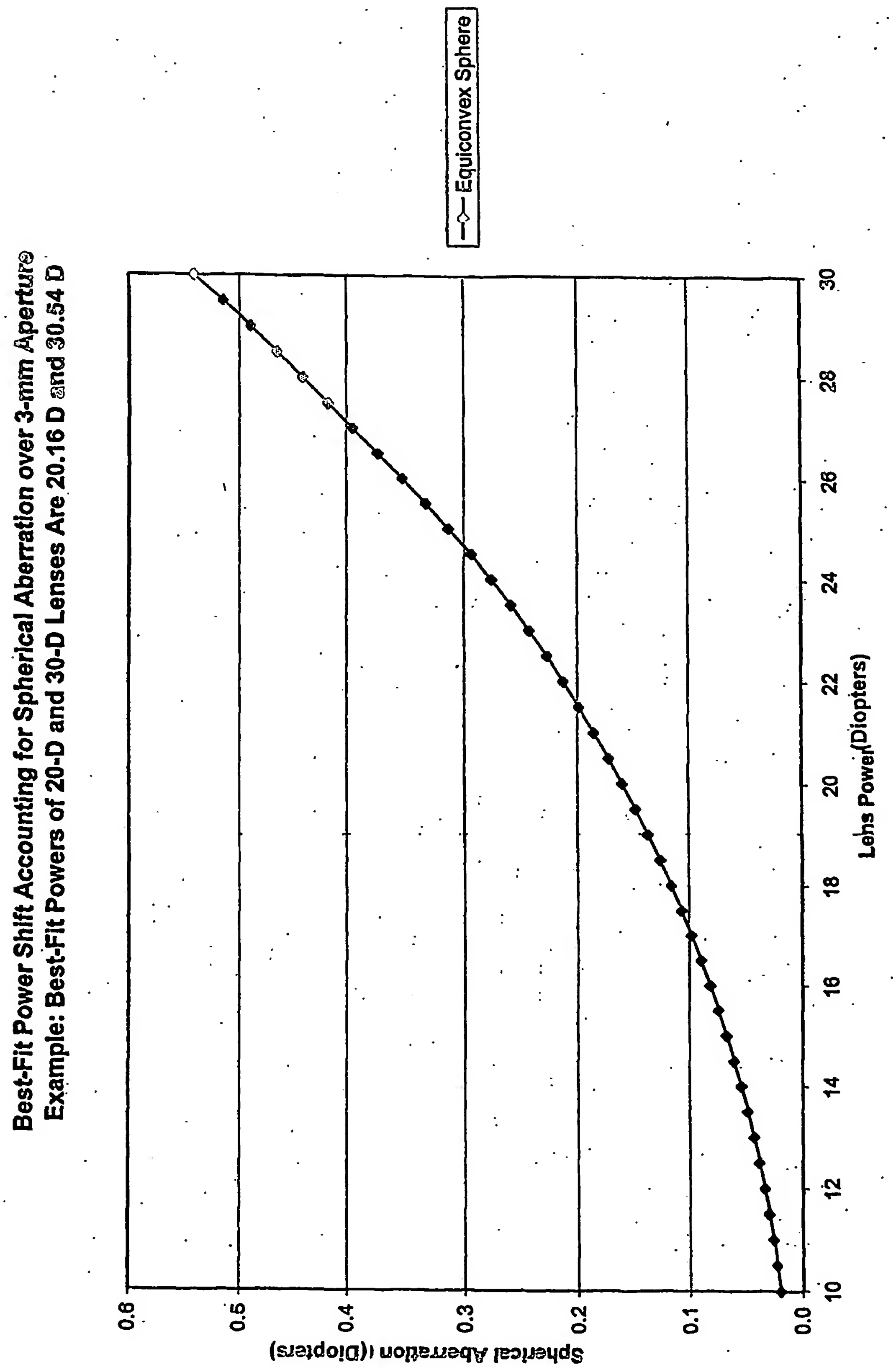

Best-Fit Power Shift Accounting for Spherical Aberration over 3-mm Aperture
Example: Best-Fit Powers of 20-D and 30-D Lenses Are 20.16 D and 30.54 D
Equiconvex Sphere
Spherical Aberration (Diopters)
0.0
0.1
0.2
0.3
0.4
0.5
0.8
Lens Power (Diopters)
10
12
14
16
18
20
22
24
26
28
30

FIG. 13

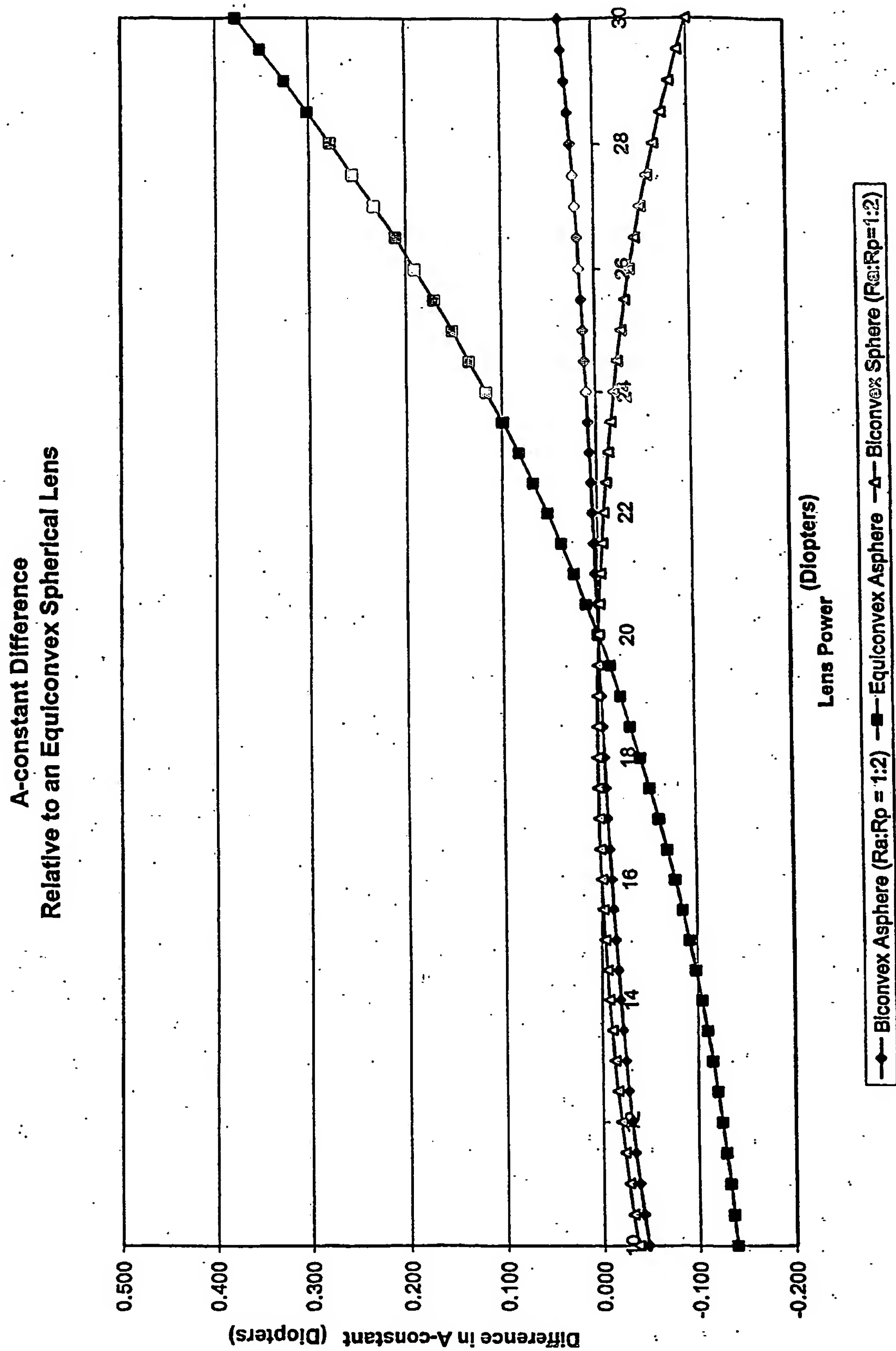

A-constant Difference
Relative to an Equiconvex Spherical Lens
Difference in A-constant (Diopters)
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
10
14
16
18
20
22
24
26
28
30
Lens Power (Diopters)
Biconvex Asphere (Ra:Rp = 1:2)
Equiconvex Asphere
Biconvex Sphere (Ra:Rp=1:2)

FIG. 14